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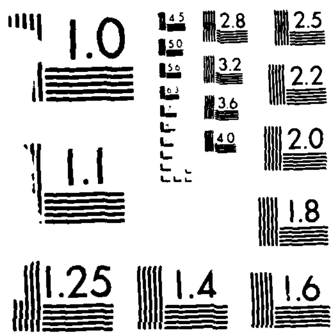

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Diesel Sprays

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

An experimental study has been made of the structure of high speed Diesel jets. A constant volume chamber has been constructed into which sprays of different liquids at a controlled pressure and duration can be injected. The chamber can be pressurized with air or nitrogen to a design pressure of 900 psi and heated to 750°F. Optical access is provided by 2 fused quartz windows for viewing the first 8 cm of the spray. The injector is electronically controlled and maintains a constant flow rate

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during the injection period. An air operated pump provides liquid injection pressures up to 10,000 psi. Microphotographs of the spray have been made using a 200 mm lens camera with extension tubes and a 0.5 μs microflash. Using a large magnification camera, photographs showed the formation of a train of surface waves and the presence of liquid ligaments issuing from the main liquid jet in the radial direction. Discharge coefficients were determined from measurements of weight of liquid during injection period. Discharge coefficients decreased with increasing injection pressure, indicating presence of cavitation in the nozzle. Injection of liquid into a coaxial stream of air with velocities up to 340 m/s allowed determination of the constant "A" in the aerodynamic theory which represents the intensity of surface perturbations before any amplification by shear occurs. A birefringent liquid for determining stress in the liquid was tested. An experiment was conducted with liquids of different vapor pressure on 5 nozzles. The results indicate that cavitation is a function of a nondimensional pressure parameter. A survey of literature and preparations for an experiment on impinging sprays was made.

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IMPINGEMENT OF LIQUID FUEL SPRAYS ON HEATED WALLS

FINAL REPORT

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Francisco Ruiz
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February 7, 1986

U.S. ARMY RESEARCH OFFICE

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STATEMENT OF THE PROBLEM STUDIED

The breakup of a high speed jet of liquid into a cloud of droplets is a phenomenon that has multiple applications in industry and has attracted the interest of investigators for a long time. The most common applications are: Diesel injection, atomization of reactants in fluidized bed reactors, fire extinction, and liquid jet mining and cutting. In some cases the purpose is to obtain a very fine spray, like in the Diesel injector. In other cases, such as projection of jets of water to fight fires from a distance, and jet cutting, the ideal is to obtain a jet as clear and free of perturbations as possible.

In previous studies of Diesel injection sprays, several mechanisms have been proposed to explain the physics of the atomization process, and attempts have been made to make quantitative predictions that are useful for design and modelling of injection systems. However, after more than fifty years of research, the basic structure of Diesel jets remains unknown. After the excellent work of Reitz and Bracco [1] at Princeton, supported by their own experimental results and those of other scientists, it has been considered that only three of the several proposed mechanisms influence spray structures. These mechanisms are: aerodynamic interaction, turbulence, and cavitation.

Aerodynamic interaction provides an explanation of the influence of the ambient gas into which the liquid is injected. The spray becomes finer and the angle is wider when it is injected into a higher pressure gas. In our own experiments [2] we have been able to check the validity of the theory including the condition of injecting into a gas that moves in the same direction as the liquid and at a higher speed so that the shear stresses are reversed. This theory cannot explain the influence of the nozzle geometry and injection pressure which, as reported by many researchers ([1] [2] [3] [4]), can be significant.

Turbulence provides a partial explanation of the influence of the nozzle geometry, even though it does not explain the effect of the gas pressure. It has not developed much from the qualitative descriptions of Schweitzer [5]. Its effects are very difficult to distinguish from those of the other mechanism, cavitation.

Finally, cavitation has been considered by several investigators as an important factor. Some experiments [1] seem to throw some doubt on the likelihood that cavitation is the main factor affecting atomization. It has, however, been observed in practical injector nozzles, when optical access to the inside of the nozzle is possible

[3]. Its effects are very similar to those of turbulence, but it depends on velocity not through the Reynolds number, but through its own parameter, which is a ratio of pressures. These three theories can be combined to form a system that can explain many of the phenomena observed in the atomization process. Aerodynamic interaction deals with conditions outside of the nozzle, while turbulence and cavitation deal with the inside. There is a requirement to match the in-the-nozzle phenomena, which includes turbulent and cavitational effects, with the out-of-the-nozzle problem, where the results of the previous problem -velocity and pressure fluctuations, spectra, void fraction- are an input. The model which relates all three phenomena can be described as follows:

1. The liquid separates from the sharp nozzle inlet. It can be roughly considered as ideal flow and axisymmetric.

2. A vena contracta is produced in the orifice, the remainder of the orifice cross-section is occupied by vapor forming a cavity. The pressure in that cavity is the vapor pressure of the liquid. The cavity wall is perturbed by profuse boiling at the surface. That perturbation can be modeled as a random distribution of spherical bubbles opening into the cavity space.

3. The flow reattaches to the nozzle wall - a process similar to that of a hydraulic jump. Pressure increases, and velocity decreases. There is a loss of pressure head which can be calculated. That loss of energy is transformed into turbulent fluctuations at the boundary layer, which is fairly thick. This boundary layer also entrains a substantial amount of vapor from the cavity, which is replenished by boiling. The fluid outside the boundary layer remains ideal.

4. Since the turbulent energy flow into the boundary layer is far greater than that for fully developed conditions, the turbulent kinetic energy decreases by dissipation as it is convected downstream. At the same time the vapor bubbles that were entrained into the liquid at the reattachment region collapse, generating a roughly spherical velocity field around each one of them which further feeds the fluctuation energy.

5. This process of turbulence decay and generation continues along the nozzle until the exit. Outside, the aerodynamic shear amplifies the surface disturbances and breaks up the liquid jet. Considering Taylor's short wavelength theory, the dispersion relationship is fairly flat, and so the waves that are generated depend very much on the turbulence spectrum at the nozzle exit is. In this way the initial spray droplet size is in direct relationship with the turbulence spectrum.

6. Further downstream, other long wavelength instabilities develop in the spray core, that lead to the development of "Christmas tree" or "herringbone" patterns in the spray.

By this means the separate theories can be combined to explain the observed

phenomena to predict the enhancement of atomization with increased injection pressure, independently of air shear. It also shows how a long orifice can produce a more stable jet: there is turbulence, but it decays along the orifice. The purpose of the model will be to predict the value of the "constant A" of the aerodynamic theory, as a function of geometry, fluid properties, Reynolds number and cavitation parameter.

EXPERIMENTAL APPARATUS

This research has been oriented towards the assessment of these three theories, in order to ascertain in what way can they be combined to explain the physics of high speed liquid atomization. For that purpose, a constant volume chamber has been designed and constructed into which sprays of different liquids at a controlled pressure and duration can be injected. The chamber is filled with air or nitrogen gas at a high pressure and ambient temperature. The chamber has been designed to operate at 750 degrees F, and does have the heating capability to reach that temperature at the design pressure of 900 psi. Optical access to the spray is possible through two fused quartz windows, diametrically opposed on the side wall of the cylindrical chamber, covering the first 8 cm of the spray. Under normal operating conditions in a Diesel engine, the liquid would impinge against the piston before that distance. The injector is electronically controlled and maintains a constant flow rate during most of the injection period. An air operated pump provides up to 10,000 psi of constant pressure for the liquid for small continuous flows or single injections. Details of the experimental apparatus are shown in Figures 1, 2, and 3.

At the present stage, the system is being prepared to achieve real Diesel engine conditions of pressure and temperature, in order to analyze the impingement of the spray onto a transparent quartz plate. A spark system has been built to ignite a mixture of nitrogen, oxygen, and combustible gas prior to the injection of the liquid. In this way high pressures and temperatures are attained without having to externally heat the chamber for a long period of time.

The principal technique used in this experiment has been macrophotography: pictures were taken using a 200 mm lens camera with extension tubes, on 35 mm Kodak technical pan film. The spray was illuminated from behind using an E.G.&G. microflash, with a pulse duration of 0.5 microseconds. The light was diffused by a translucent plastic screen, placed between the spray and the flash, inside the

chamber. Magnifications of 1.5 times were obtained in the negatives, while maintaining the very good resolution of this film. In a single picture, photographs cover a length of the spray or about 100 nozzle diameters. This is what is normally required to see the completion of the atomization process.

The constant volume combustion chamber (CVCC) has been modified so that a pre-mixed mixture of methane, oxygen and nitrogen can be combusted before the liquid injection. This will raise the ambient temperature to the levels found in diesel engines at the time of injection. A vacuum pump and gauge will be used to allow the CVCC to be cleaned in between runs.

Leaks in the window packing material have been fixed. The electrical feed for the heater was replaced with a higher current model. The electric heater was also replaced. An electronically controlled spark ignition system was made from automotive parts. A water cooled quartz pressure transducer was obtained from Cummins Engine Co. Parker Hannifin donated a number of bellows valves and fittings for the gas mixing apparatus. A high accuracy pressure gauge for determining mixture stoichiometry was purchased.

SUMMARY OF RESULTS

During the three years of the contract, two years were devoted to the design and construction of the experimental apparatus, and the third year to perform several experiments. These experiments involved measurements of spray angle, jet intact length, instability wavelength, and discharge coefficient of the nozzle, for different conditions of injection and chamber pressure, different liquids, and different nozzle geometries. Techniques, such as laser in-line holography, and flow birefringence were tested. The following results were obtained:

Photography

Considerable effort was devoted to find a photographic technique to provide as good a detail as possible of the spray. The problem was difficult because of the high velocity (150 m/s), small size (0.3 mm diameter), short duration (order of msec), and difficult access to the spray. A very long bellows camera (10 ft) was used successfully to obtain magnifications up to 12 times in the negatives on 4x5 Tri-X film. However, problems due to the difficulty of focusing, the need to have two people to operate the system, and the limitation in pictures that could be taken and developed at one time discouraged us from following this line. We found it best to use a 35 mm camera and a smaller magnification, which allowed use of a film of greater resolution, and the system could be operated by just one person. Some

details of the jet before breakup occurs were discovered with the large magnification camera, such as the formation of a train of surface waves, and the presence of liquid ligaments issuing from the main liquid jet in a roughly radial direction.

Discharge Coefficient

The discharge coefficient of a standard Diesel injection nozzle was measured by weighing the liquid injected during a determined lapse of time, extended over a large number of injections to obtain the average. In order to eliminate the influence of the unsteady phases of the flow, at the beginning and at the end of the injection, results were obtained for different injection durations. The process was repeated for different injection pressures, from 1000 to 7000 psi, with injection into the ambient atmosphere, out of the chamber. The discharge coefficient as a function of injection pressure is plotted in Fig. 5. Contrary to what is expected for a non-cavitating orifice (see ref. [6]) the discharge coefficient decreases with an increase in the injection pressure. This is evidence of cavitation at least for the conditions of the experiment.

Coaxial Air Jet Experiments

In order to separate the aerodynamic interaction effect from other effects, the liquid was injected into a coaxial stream of air, which was established a few miliseconds before, and shut off shortly after the photographs were taken, to prevent a change in the chamber pressure. The air stream was in some cases faster than the liquid jet (110 to 200 m/s for the liquid, up to 340 m/s for the air) so that the shear stresses that are caused by this interaction would be reversed (Fig. 6). Measurements of the spray angle were made from the photographs, and related to the aerodynamic interaction theory. Details can be found in [2] and [7]. Even when the stresses had a direction opposite to the usual, the behavior of the spray angle was conform with the theory. A very strong influence of parameters not included by the theory -absolute injection pressure, nozzle geometry- was also found. Plots of the non-dimensionalized spray angle against a parameter related to the theory are shown in Figs. 7 and 8. "A" is a constant in the aerodynamic theory which represents the intensity of surface perturbations, before any amplification by shear occurs.

Birefringence Technique

A novel technique based on flow birefringence was tested in the apparatus. Some liquids have the property of becoming birefringent when subject to stress. If such a liquid is analyzed with polarized light, fringes appear according to the difference between the principal direction stresses in that part of the fluid. Then, from the rheological properties of the fluid these stresses can be related to the

velocity field. Since this experiment involves very large stresses for a very small size, this technique, when sufficiently developed, would allow determination of the velocity profile in the liquid jet, before atomization occurs.

First, two solutions of surfactants were tested as birefringent liquids. The viscosity and other properties were very similar to those of the fluid used for the previous experiments: 95 cp, however, their sensitivity to stress birefringence was not sufficient. Later, a colloidal solution of the commercial dye Milling Yellow NGS was used, for which there exists an extensive literature on its birefringent properties [8]. This time the sensitivity was high enough and we were able to obtain some photographs with fringes in them. Unfortunately, this time the liquid reacted with the material of the injector and other metallic parts, causing them to rust rather quickly. At the same time, the reaction caused the solute to precipitate and the solution lost its important properties. We had to remove the liquid and flush our injection system. This technique could be made to work if the part of the dyestuff that causes the corrosion is removed (it contains salt), or it is used in an apparatus that is resistant to it.

Laser Techniques

An attempt was made to use the Malvern particle sizer in this experiment. The new parallel-sampling Malvern, which can measure the intensity on all the diode rings of the instrument at the same time and thus give instantaneous measurements of particle size in unsteady sprays, was made available to us for a few days. The results were disappointing: the normal light obscuration in the region of the spray that is of interest in was too high: over 90 %. The software assumes a single scattering mode and so the results of the computation that the apparatus performs internally are not reliable. A new multiple scattering model has been developed at Sheffield by Felton [9]. It can be tried in similar conditions to obtain Sauter mean diameter, though it is not reliable for predicting the scatter of the droplet distribution.

We also tried to obtain an in-line hologram of the spray, outside the chamber. The laser used for this was a pulsed ruby laser, synchronized with the spray. The laser proved to be highly unreliable: at times the pulse duration was in the order of microseconds, while at other times in the order of milliseconds.

Vapor Pressure Parametric Study

After the experiment of the coaxial air jet had provided information about the effect of aerodynamic interaction, we devised an experiment to assess the importance of cavitation versus turbulence. This time, two different fluids were tested under the same conditions. One of them was a commercial vacuum pump oil, which has a vapor pressure at 50 degrees C smaller than 0.0001 torr. The other one was a mixture of 80 % glycerin with 20 % methanol by volume, which had almost the same kinematic viscosity as the oil, but a vapor pressure at 24 degrees C of 29.5 torr, much higher than that of tne oil. The properties of these liquids are summarized in Table 1. Five different nozzles were used this time:

1. Standard: 0.008 inches in diameter. Length/Diam. = 3.3, provided with a control needle just upstream of the orifice.

2. Nozzle I: 0.28 mm diam. L/D = 3.26. No needle.

3. Nozzle II: 0.5 mm diam. L/D = 2.1. No needle.

4. Nozzle III: 0.355 mm diam. L/D = 0.2 (sharp edge). No needle.

5. Nozzle IV: 0.4 mm diam. L/D = 78 (long tube). No needle.

All nozzles had sharp inlet corners. Nozzle IV inlet was a Borda mouthpiece.

Spray angles, jet intact lengths, instability wavelengths, and discharge coefficient into the atmosphere were measured as described before for all these nozzles using the two liquids. Almost no difference was found between tests made with the two liquids. This confirmed the hypothesis that the effect of cavitation must be a function of the nondimensional quantity (injection-pressure - vapor pressure)/(injection-pressure - chamber gas pressure) and not a direct function of the vapor pressure. Indeed, if such were the dependence, sprays with each of the two liquids would have to be very different in properties, contrary to our experience. If cavitation is covered by the parameter discussed above, then it should have been the same for both fluids since, when we subtract a vapor pressure in the order of torr from an injection pressure in the order of thousands of psi, then the value of vapor pressure is totally negligible and has no influence. This cavitation parameter would always be smaller than the critical value for cavitation to occur for sharp inlet nozzles. For other geometries, cavitation will occur or not according to the value of the pressure parameter.

Impinging Sprays

Some data is shown in Figs. 9 to 11. More information can be obtained in ref. [10]. These data will be analyzed in depth in order to extract information on droplet size and more insight into the physical structure of the sprays.

The survey of the literature that pertains to impinging sprays was divided into four subcategories; single drops hitting a hot plate with low ambient pressure, sprays hitting a hot plate with low ambient pressure, single drops hitting a hot plate with high ambient pressure, and sprays hitting a hot plate with high ambient pressure.

A considerable amount of research about single droplets hitting a hot plate is reported in the literature. Gottfried, Lee, and Bell (11) performed an extensive analysis of the Leidenfrost phenomenon. The Leidenfrost phenomenon occurs when a drop becomes suspended on a vapor film above a heated plate. The total evaporation time of a given size drop steadily decreases with increasing plate temperature until the Leidenfrost point where the evaporation time suddenly increases. Wachters and Westerling (12) demonstrated that the behavior of a drop hitting a heated plate will depend on the droplet velocity, or more generally, the drop Weber number. At low Weber numbers, the drop rebounds intact from the heated plate. At higher Weber numbers the drop breaks into many smaller drops. Andreyev and Borishanskiy (13) noted that the measured Leidenfrost temperature of a particular liquid depends on the material properties and the surface roughness of the plate. A plate material with a low thermal diffusivity will have a higher Leidenfrost temperature than a material with a high thermal diffusivity.

Water sprays are commonly used to cool high temperature metal surfaces. The variables of interest are the heat flux and the water flux. Hoogendoorn and den Hond (14) found that the Leidenfrost temperature was higher than for single drops and that it also depended on the water flux. Increasing the water flux increased the Leidenfrost temperature. They also found drop interaction was important. Models for spray cooling based on single drop results would give erroneously high values of heat flux.

Very little work has been done with single drops hitting a heated plate under high ambient pressure. High pressure refers here to an ambient pressure near or above the critical pressure of the liquid. Temple-Pediani (15) investigated a large range of pressures and temperatures for a single droplet evaporating on a heated plate. Temple-Pediani made measurements of drop lifetimes versus plate temperature

for a constant initial drop size. He found a characteristic jump in the drop lifetime at the Leidenfrost temperature when performing the experiment at 1 atmosphere ambient pressure. However, with increasing ambient pressure the increase in drop lifetime decreased and the Leidenfrost temperature moved higher. When the ambient pressure neared the critical point of the liquid the Leidenfrost point disappeared. The drop lifetime became a decreasing function of plate temperature until a plate temperature about 60 °C above the critical temperature of the liquid, at which time the drop lifetime remained constant.

Research results pertaining to sprays hitting heated plates in a high pressure environment are few. Two studies (10) (17) used sampling valves to determine soot concentration profiles in an operating diesel engine. The location of the sampling was varied from near the injector to near the piston bowl. The results show that soot is produced in large quantities in fuel rich areas. Less can be said about soot oxidation since the sampling valves could not be moved to follow the motion of the piston. There is also some uncertainty about the result due to the intrusive nature of the sampling probe and the reliability of sampling solid particles with a sampling probe. Nothing was mentioned about the impaction of the spray on the piston bowl.

Hori and Sugiyama (18) studied fuel sprays in an operating medium swirl diesel engine using high speed movies and gas sampling valves. They observed that the fuel spray hit the piston bowl. They found that the residence time of the fuel film on the piston bowl was a function of the in-cylinder air motion. They also observed that the fuel film spilled over into the clearance volume and back along the piston towards the injector.

Kamimoto et al (19) investigated the heat transfer from an impinging diesel spray. Using n-tridecane they observed that drops hit the flat plate when the injector was placed 28 mm from the plate. However, at a distance of 48 mm, no drops were seen hitting the plate.

FIGURES AND TABLES

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PARTICIPATING SCIENTIFIC PERSONNEL

Dr. Norman Chigier, Principal Investigator
Francisco Ruiz, M.E., May 1985, currently working on a Ph.D.
James Zurlo, currently working on a Ph.D.

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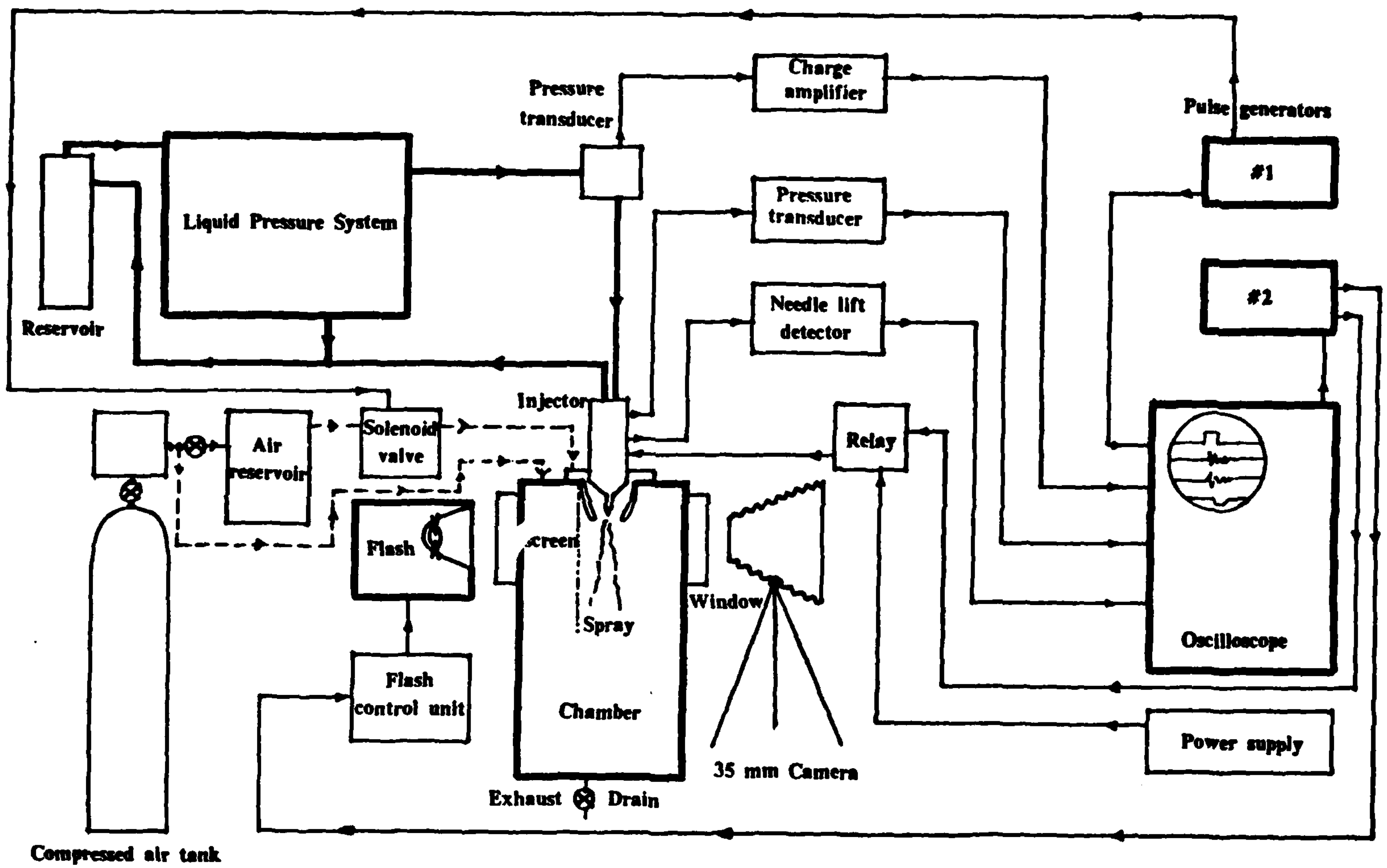

Fig. 1. Diagram of the experimental apparatus.

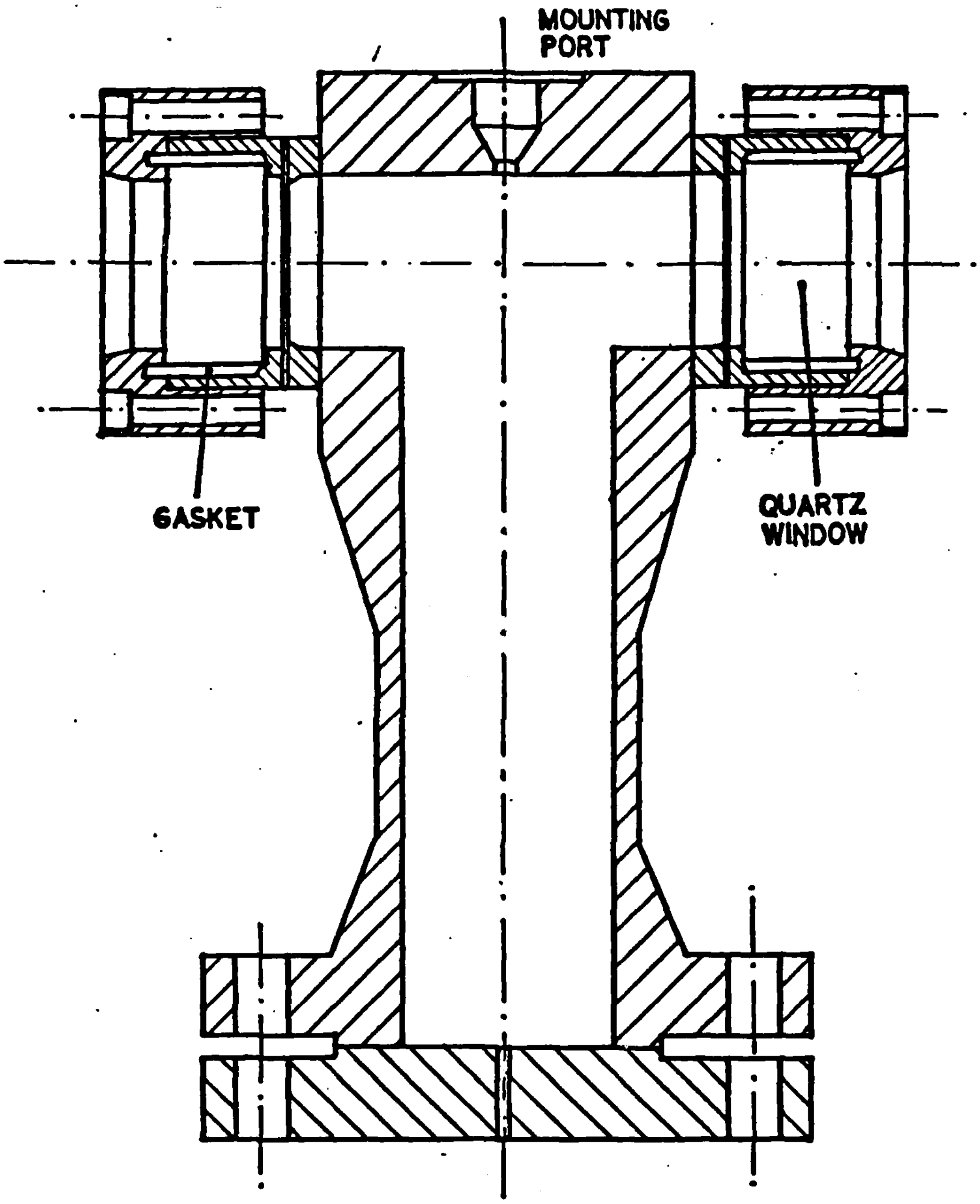

Fig. 2. High pressure chamber.

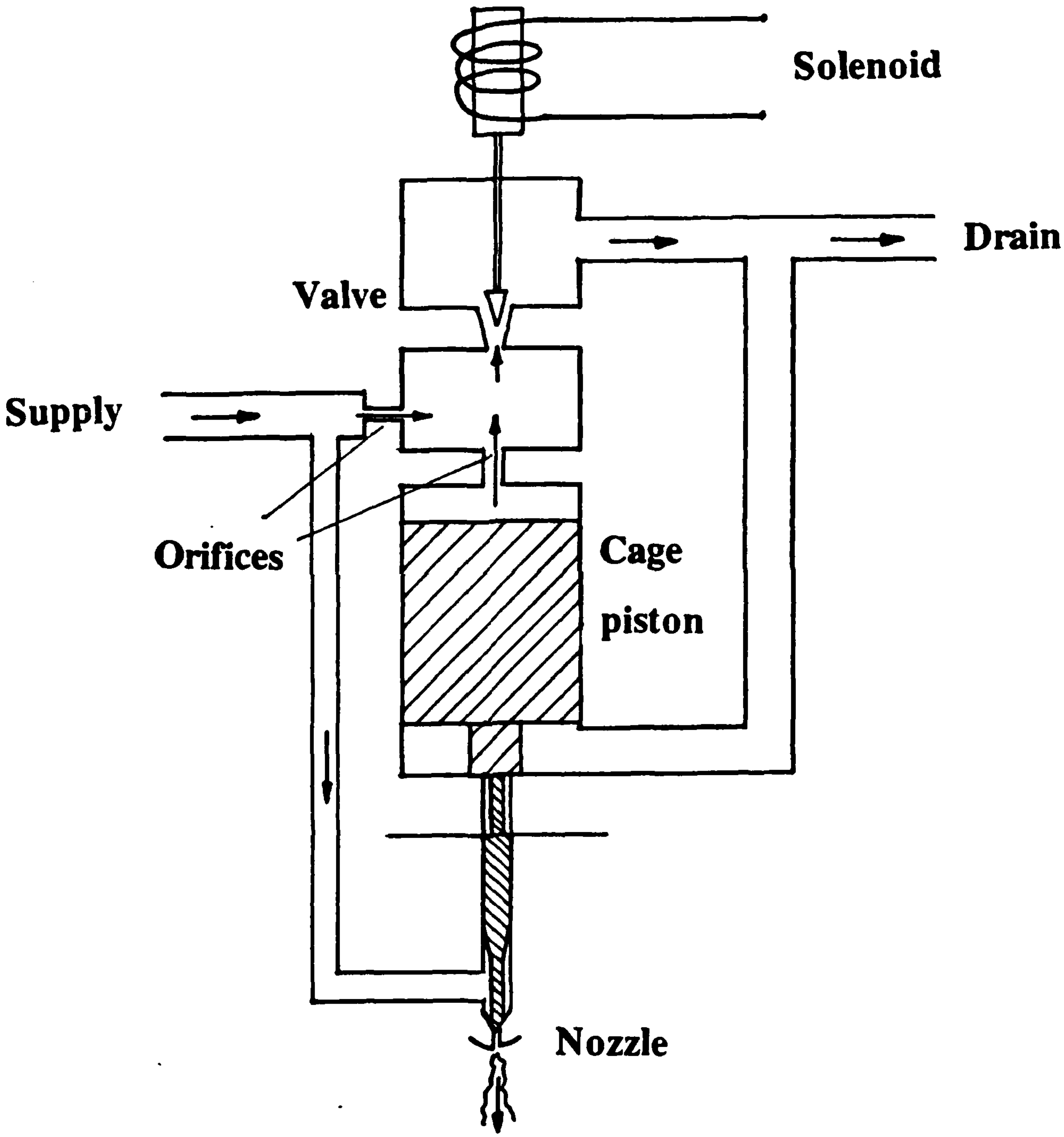

Fig. 3. Schematic of the injector.

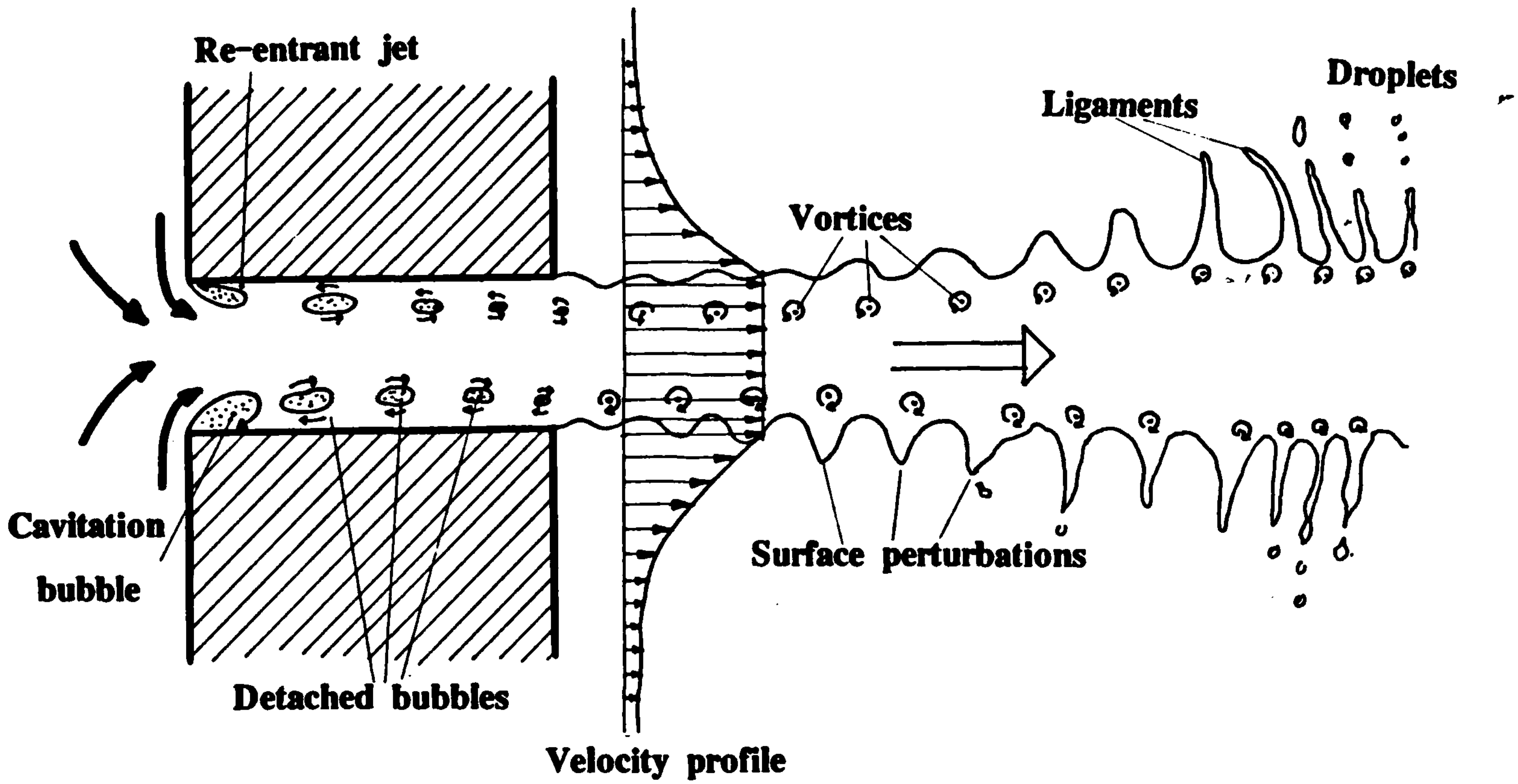

Fig. 4. Diagram of the physical model.

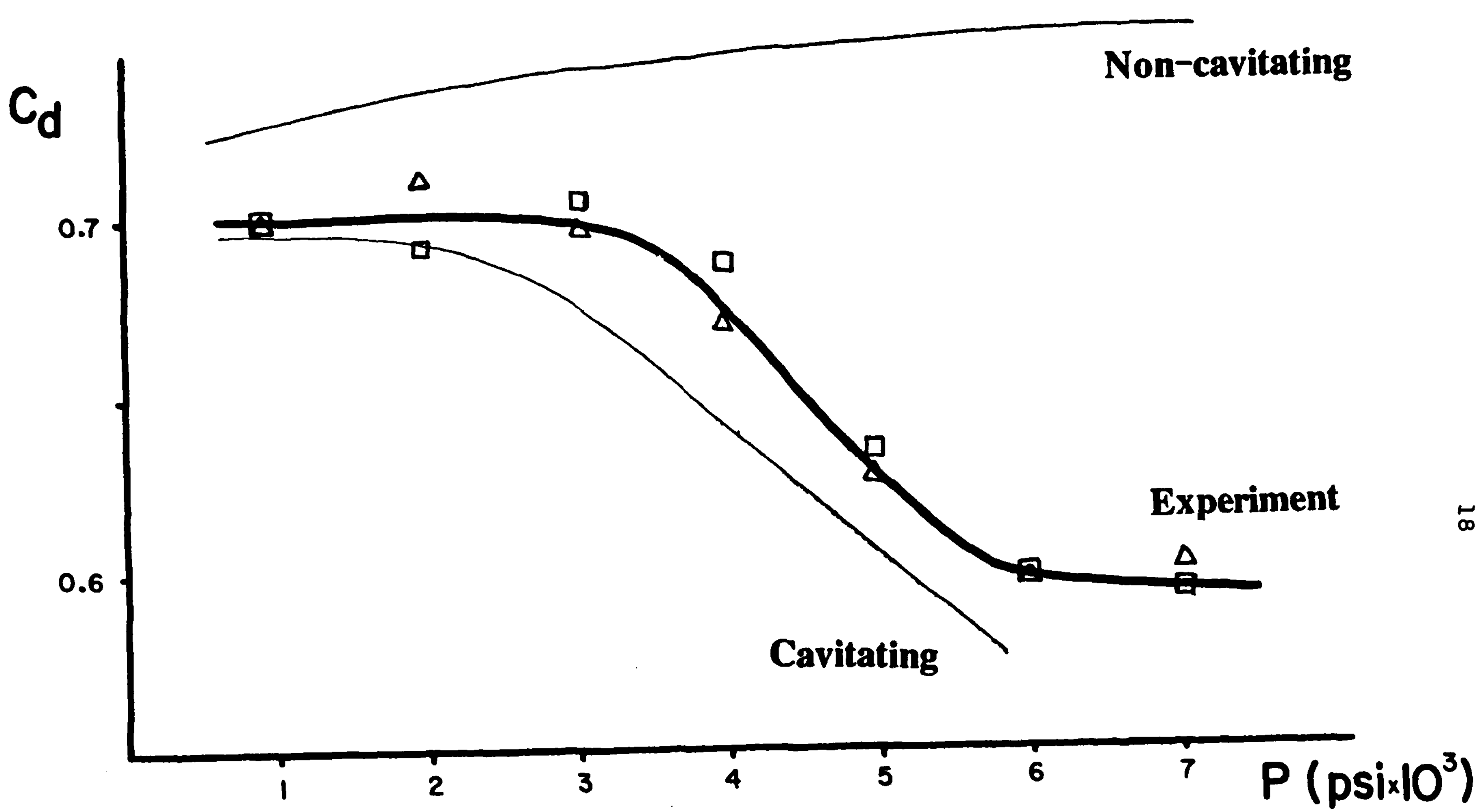

Fig. 5. Discharge coefficient vs. Reynolds number.

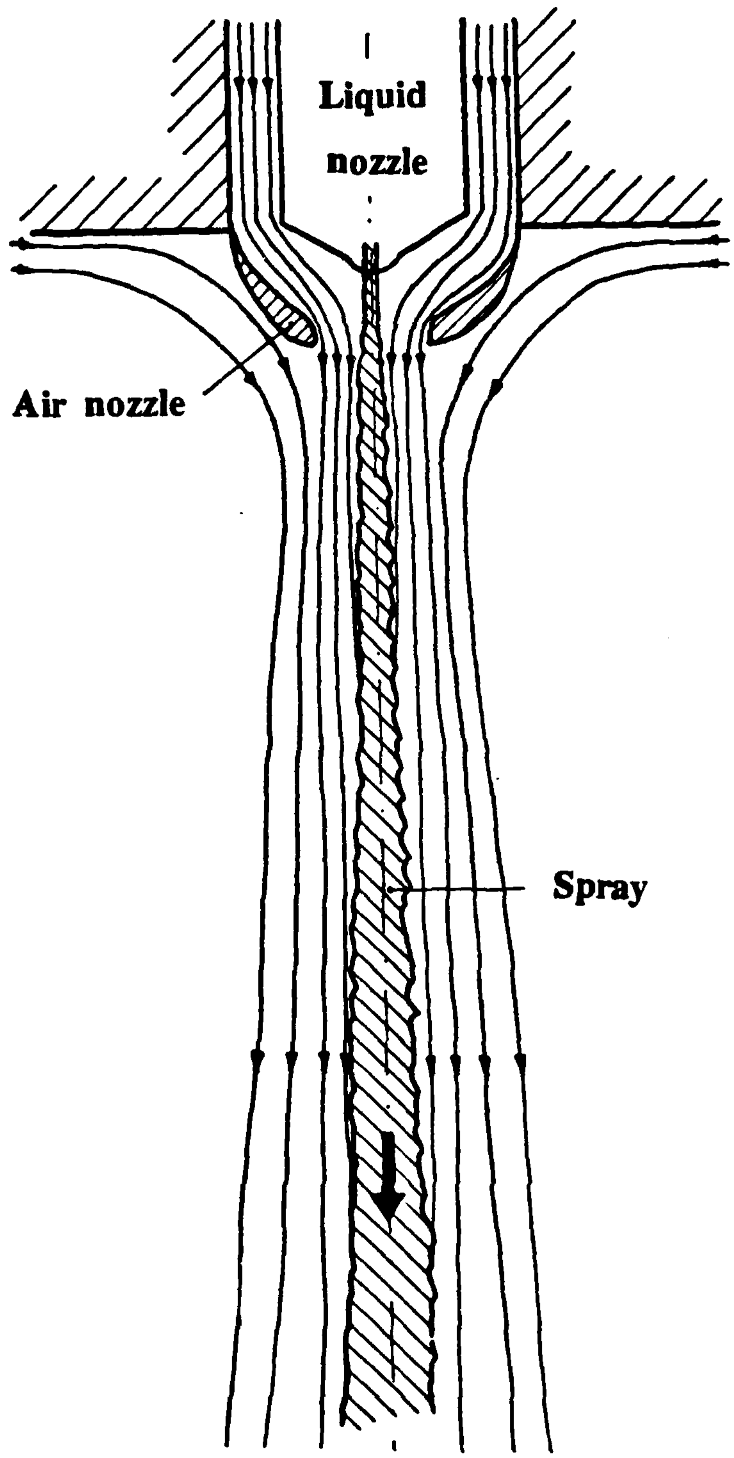

Fig. 6. Diagram of the coaxial gas jet.

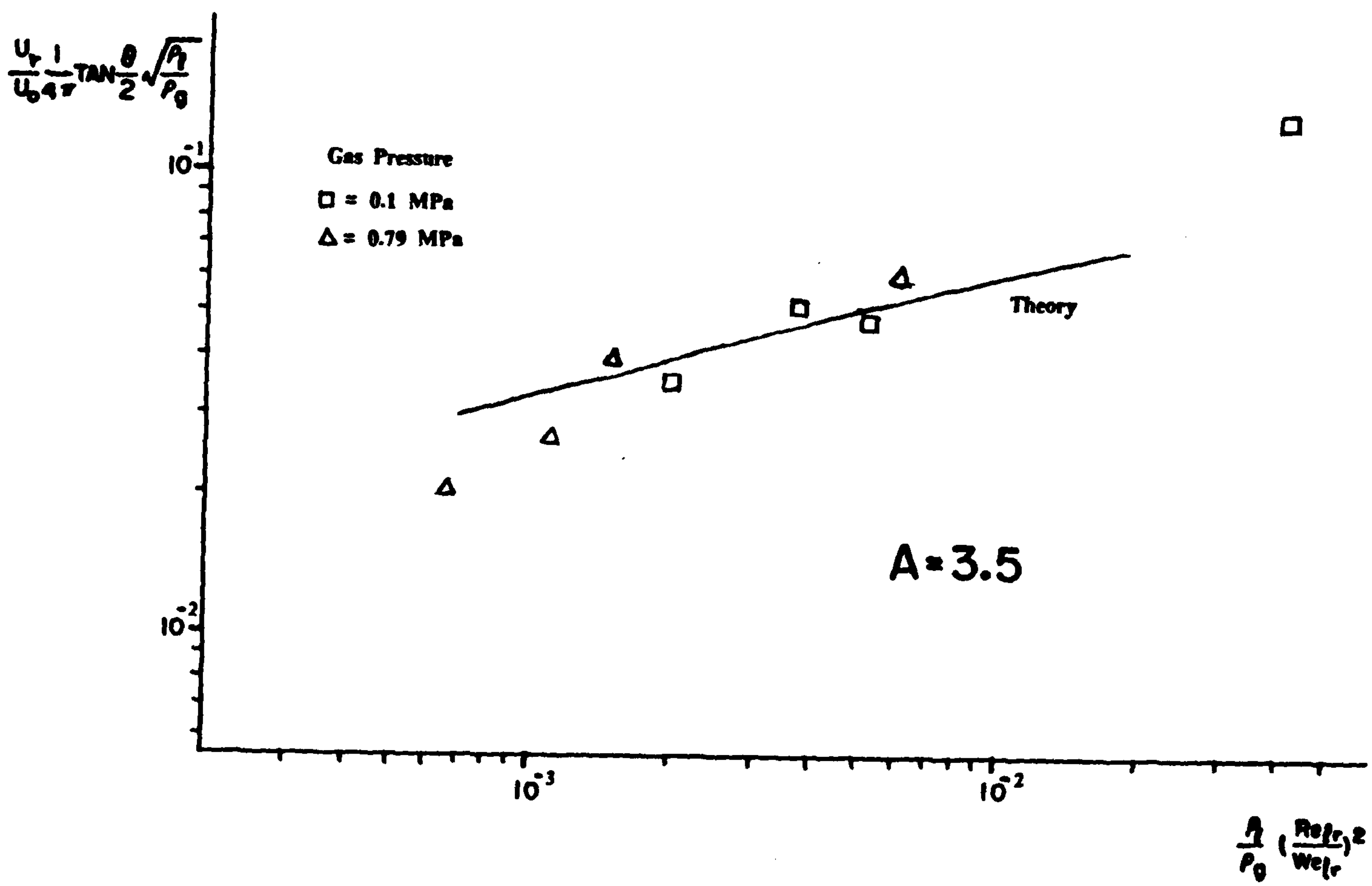

Fig. 7. Nondimensional spray angle variation. Velocity 150 m/s.

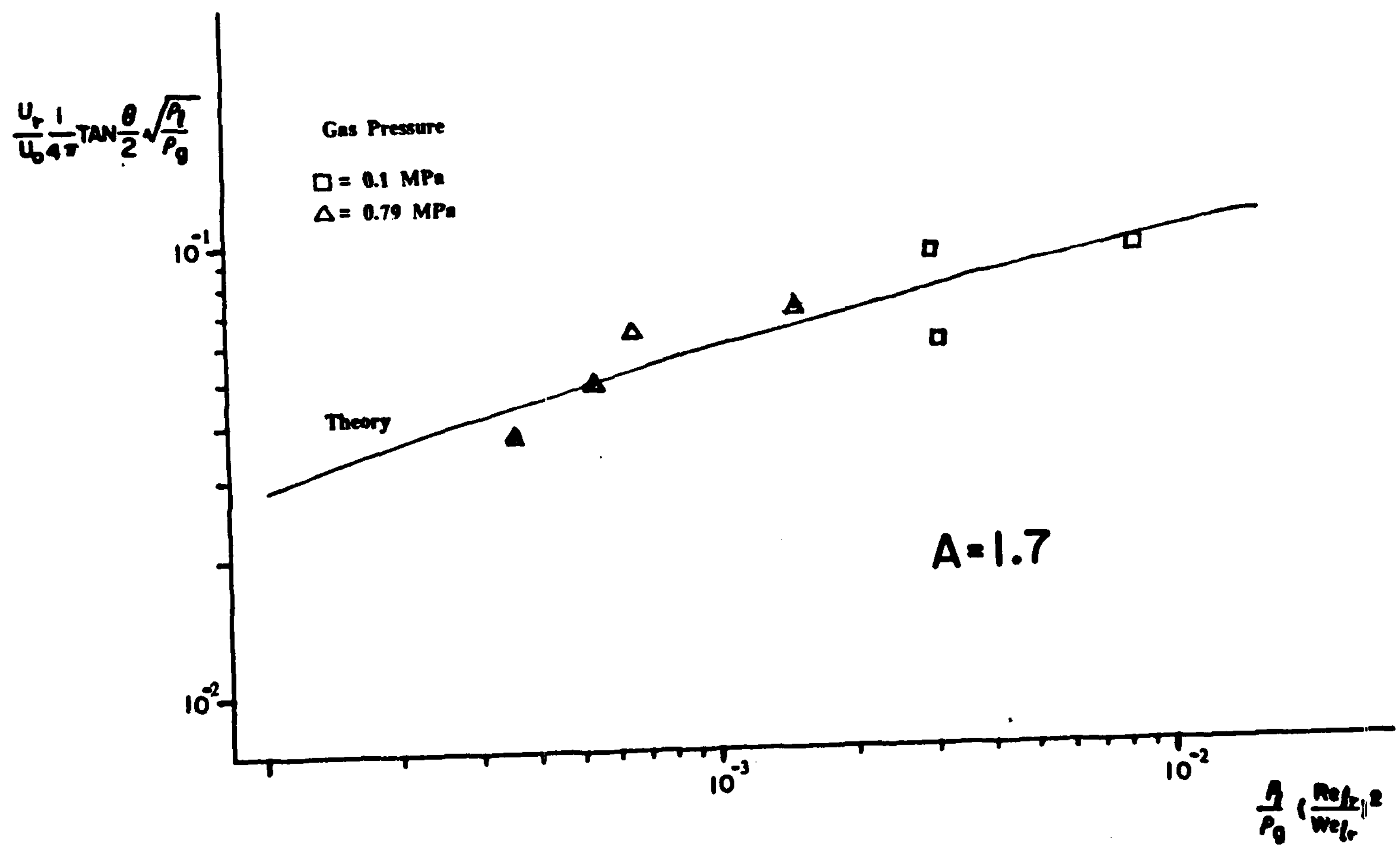

Fig. 8. Nondimensional spray angle variation. Velocity 200 m/s.

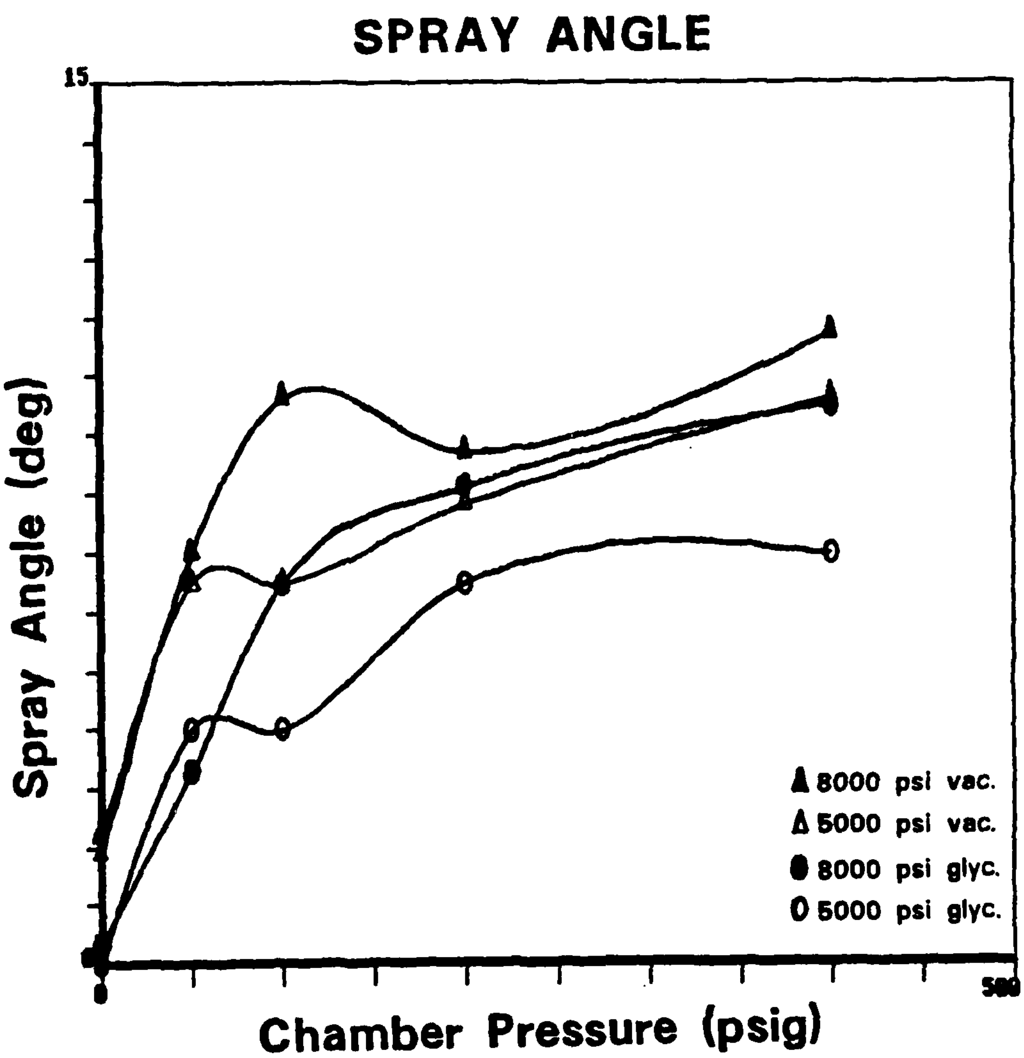

Fig. 9. Spray angle vs. chamber pressure. Two liquids.

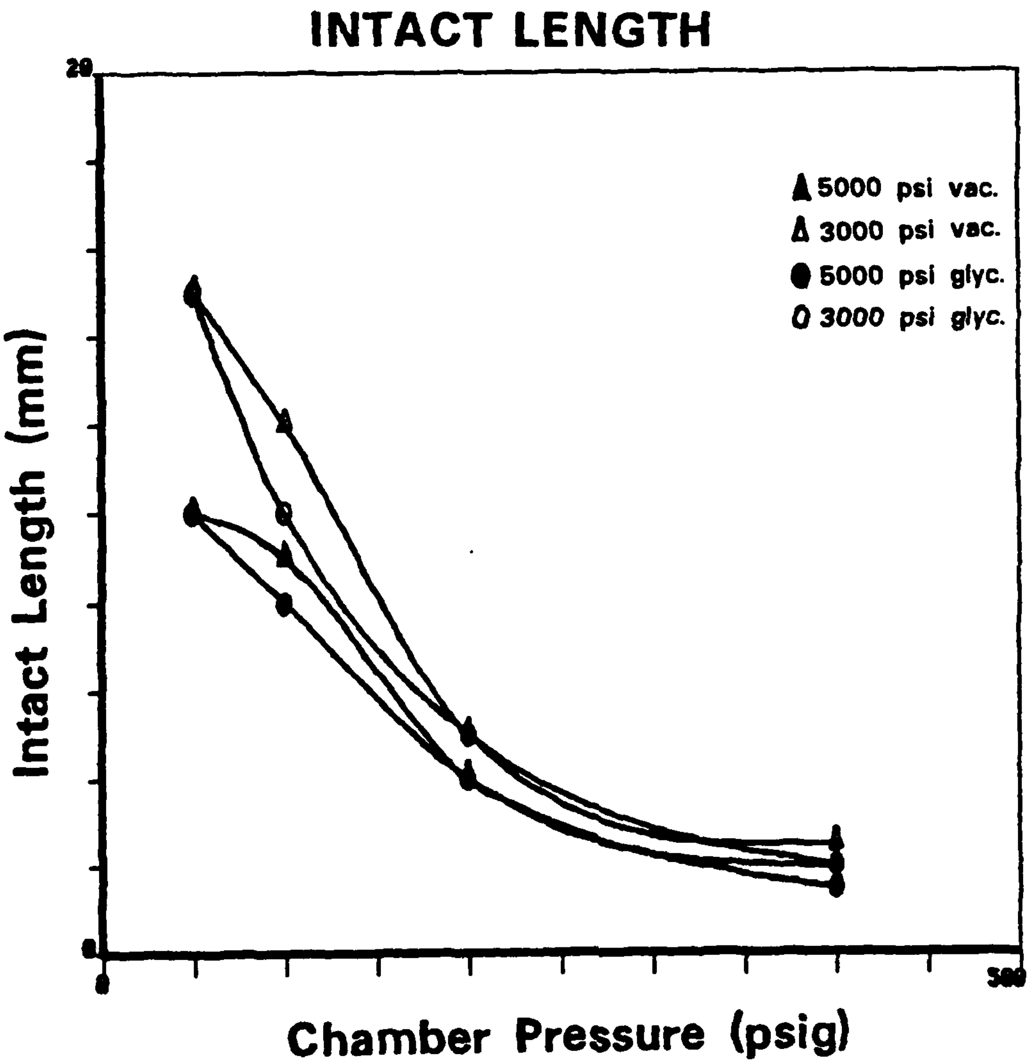

Fig. 10. Jet intact length vs. chamber pressure. Two liquids.

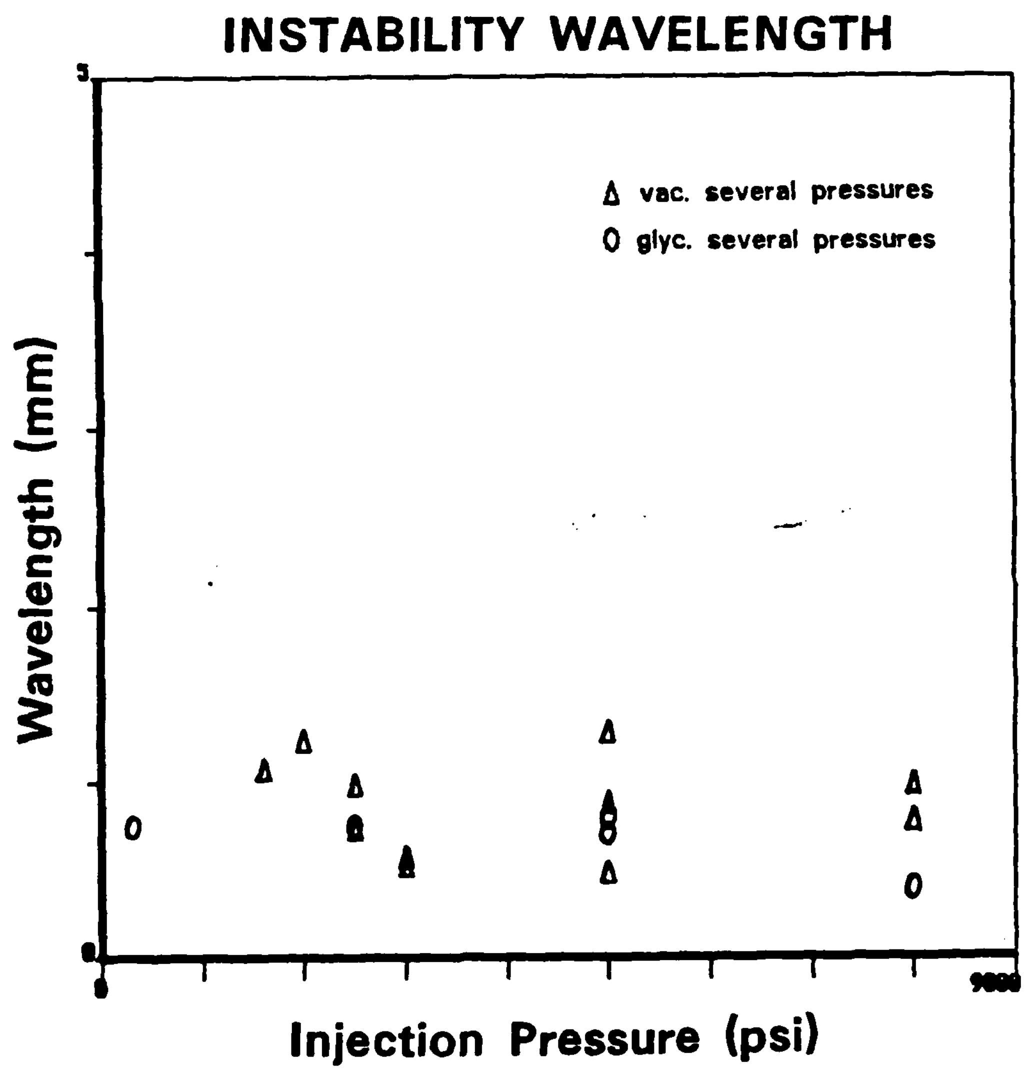

Fig. 11. Surface Instability wavelength vs. injection pressure. Two liquids.

Table 1. Properties of the liquids used in the experiments.

FLUID PROPERTIES

(at 24 deg.C)(S.I. units)

	Kin. Visc.	Density	Surf. Tens.	Pv (torr)
Vacuum Oil:	1.701	0.822	28.36	< 1E-4
80% Glyc.+ 20% Meth.:	1.512	1.098	38.63	29.5

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